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An energy saving approach in the manufacture of carbonated soft drink bottles

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Abstract

The use of plastics for packaging has been increasing steadily over the years. Polyethylene terephthalate (PET) dominates the carbonated soft drinks (CSDs) market as the main material used in this application due to its toughness, clarity and superior barrier properties. Currently, the CSD bottles constitute 40% of the global PET consumption. PET bottles demonstrate favourable life cycle inventories compared to alternative packaging materials such as aluminium and glass. Manufacturing of the bottles starts with the production of PET resin from petrochemicals. The PET resin is then melted and injected into a preform mould which has the shape of a test tube with a threaded neck. Subsequently, the preform is heated to a certain temperature, and stretched and blown simultaneously to take up the shape of the bottle mould. Each of these steps requires energy. In this study, we will focus on the environmental footprint of CSD bottles and demonstrate that light-weighting of CSD bottles through a new bottle/preform design brings about energy reduction and greenhouse gas savings.

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Keywords: Polyethylene terephthalate bottles; weight reduction; energy savings

1. Introduction

Global PET packaging industry in 2011 is estimated to be $30.7 billion and it is set to be worth $42 billion by 2015 with an annual increase of 6.5 % [1]. Demand for PET material was 15.3 million tons in 2009 and expected to grow at a rate of 4.9% annually up to 2020 [2]. Increased use of PET in packaging industry is due to (i) technical performance achieved by new developments in barrier technology, hot-filing and aseptic packaging techniques (ii) ease of recycling (iii) superior visual appearance compared to other packaging materials. PET packaging either in rigid or flexible form offers improved economics of manufacturing compared to glass, favorable life-cycle-analysis, and most importantly light-weighting potential. PET is now widely used in packaging detergents, cosmetics, pharmaceutical, food, as well as drinks such as beer, wine, milk, ready to drink tea, juices, energy drinks, mineral water and CSDs. The CSDs are the largest end-use sector for the PET packaging. The study undertaken here aims to demonstrate the benefits of light weighting 1.5 litre CSD bottles from a current 40 g down to 37 g. It elucidates how such weight reduction brings about energy savings and the subsequent reduction in green house gases without jeopardizing the functionality of the bottles.

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2. Experimental

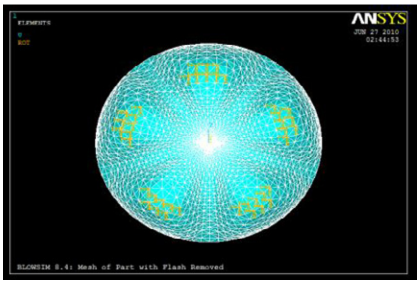
2.1. Processing of PET bottles

PET bottles are usually produced in either one-stage or two-stage injection stretch blow molding (ISBM) machines. The process starts with injection molding of a tube-like ‘preform’. The preform is stretched axially by a stretch rod and radially by pressurised air until it takes up the shape of the bottle mold. During the blow stage, a pre-blow is applied to prevent the axial stretch rod contacting the inside of the preform which may result in defects in the bottle. When the rod reaches the bottom of the container, a high blow pressure is applied to impart intricate details of the bottle mold and to improve the cooling efficiency. In the two-stage ISBM process, injection molded preforms are stored until subsequent blow molding at the bottle filling stage. Hence, the preforms require reheating; whereas in single-stage ISBM process, injection molded preforms are shaped into bottles once the preform temperature reaches just above its glass transition temperature without the need for reheating [3]. During ISBM process, PET molecules undergo biaxial orientation and associated strain hardening. The biaxial orientation of PET molecules directly influences mechanical and barrier properties of the bottles [4]. Strain hardening, which is temperature and strain rate dependent, provides a self-levelling effect on the stretching preform which is important in achieving uniform wall thickness. Therefore, control of process conditions together with the preform design provides a means to achieve the required bottle quality.

2.2. Modelling

There are various simulation studies which optimize preform shape and process conditions. Such modelling studies are mainly motivated by reduced part development time, reduced tooling cost and improved part quality. One of the recent simulation studies demonstrates a new design approach to predict optimal preform geometry and optimal operating conditions for the stretch blow molding [5]. Integrative simulation study presented here aims to reduce the PET resin used in CSD packaging by reducing the preform weight in a systematic manner. The ISBM process simulation of the bottles was followed by a virtual structural analysis to assess the performance of the PET bottles. The preforms of differing weights were virtually stretched blown into 1.5 litre CSD bottles by means of a commercial simulation software ‘BlowView version 8.4’[6]. The resultant thickness profile of the bottles and the microstructure dependant material properties were input into ‘ANSYS’ finite element software [7] in order to assess on the structural performance of the bottles in terms of the top-load and burst strength of the bottles.

In simulation of top-load strength of the bottles via ANYSIS, the bottle is constrained on the bottle base and the load was applied on the top of the bottle [Fig. 1]. Following the application of 200 N on the top of the bottle, the maximum stresses and maximum deformation values were recorded for each bottle.



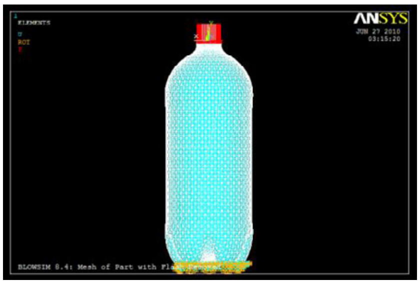


Fig. 1: Application of (a) constraints at the base; (b) the top-load at the bottle top

Similarly, in simulation of burst strength of the bottles, the top section of the bottle was clamped and the internal pressure was applied on the inner surfaces of the bottle [Fig. 2]. The maximum stresses and the maximum deformation values were recorded for each bottle under the internal pressures 1. MPa.

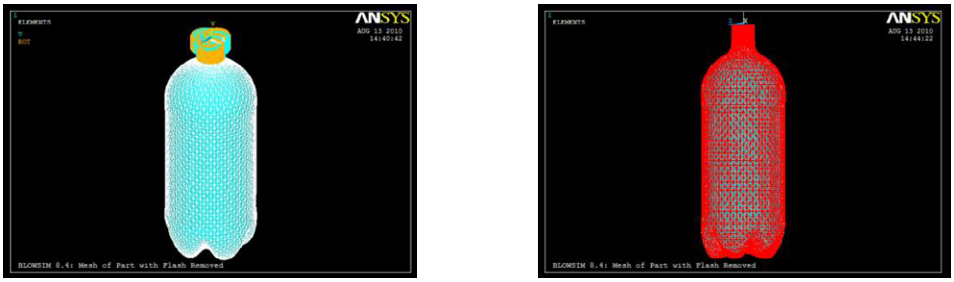


Fig. 2: Application of (a) clamps on the bottle top; (b) the internal pressure

2.3. Preform design

Preform, which is used in this simulation study, can be divided into four sections: 'finish' (threaded end), 'transition', 'body' and 'end-cap'. The transition section is further divided into two zones. For the purpose of this simulation experiment, the current finish (PCO 1810) is used and its weight is kept constant at 5.1 g for all preforms. The thickness ratio between the 'end-cap' and the 'body' of the current 40 g preform is employed to reduce the wall thickness of preform across the transition zones and the body. The preform transition zone and the body section are shaped like a cylinder but with different diameters at each end. Therefore, a typical section volume (x), which is representative of the body and the transition zones of the preform, is calculated by subtracting the outside frustum from the inner frustum as follows.

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Where, L_a is the length of the frustum; D_a and D_b refer to the outer frustum diameters; the d_a and d_b refer to the inner frustum diameters.

The end-cap volume is calculated by subtracting an elliptical cone from a half sphere as follows.

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(2)

where d and h refer to the diameter and the height of the elliptical cone respectively.

The resultant preform weight is found by adding the end-cap, body and transition weights together with the fixed weight of the thread (Eq. 3).

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Seven different preform designs from 37 g up to 40 g with 0.5 g increments were generated in this manner. Preform weight was reduced down to 37 g; further reductions in weight resulted in perform 'blow-outs' or 'sticking effect' where the perform sticks to the stretch rod during simulation process, preventing successful bottle production.

2.4. Experimental top-load and burst strength measurement of the bottles

Only the performance of the current 40 g bottle was assessed experimentally under laboratory conditions in terms of top-load strength and burst strength by means of a top-load tester and burst tester respectively. All other bottles of varying preform weights were simulated by Blowview and then their strengths were assessed by means of ANSYS structural simulation software.

3. Results and discussion

3.1. Thickness profiles of the bottles

The thickness profiles were obtained for all PET bottles of differing preform weights between 37 g and 40 g. However, for the sake of clarity, the thickness profiles were shown only for the lightest and the heaviest bottles (i.e. 37 g and 40 g preforms) in Figure 3. The bottle base thickness is found to be 3.24 mm for the current bottle (40 g preform), whereas it is 2.85 mm for the lightest bottle (37 g preform). The bottle base became thinner as the weight of the preform was reduced.

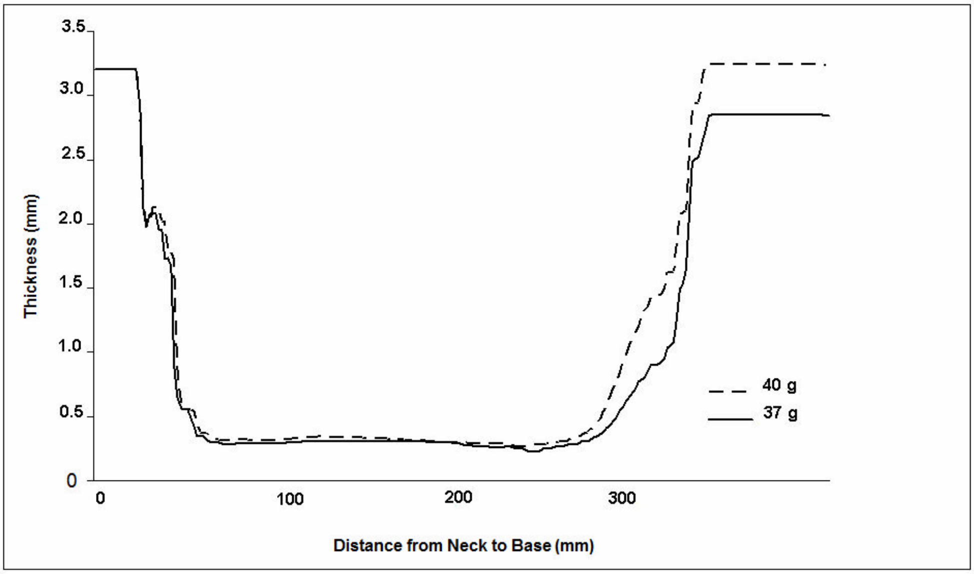

Fig. 3: Thickness profile of the bottles

3.2. Top-load and the burst strength of the bottles

The maximum stresses and displacement values were plotted at the application of 200 N top-load force for all the bottles [Fig. 4]. As the preform weight decreases the maximum stress and displacement increase. Although the 40 g preform design currently in use, results in higher top-load strength, the maximum stress observed in the bottle is not a lot different compared to the other preform designs of lower weight. The difference between the heaviest (40 g preform) and the lightest bottle (37 g preform) is rather small: at the application of 200 N top-loads, the maximum displacement differs by 7 μm, which is insignificant; and the maximum stress differs only by 200 kPa between the heaviest and the lightest bottles.

Similarly, Figure 5 shows the maximum stress and maximum displacement values at 1 MPa pressure on the inner surfaces of the bottles of differing preform weights. As the preform weight decreases the maximum stress and maximum displacement increase. The maximum stress and the maximum displacement values obtained for the light-weight bottles are much lower than current 40 g preform bottle. The difference between the heaviest (40 g preform) and the lightest bottle (37 g preform) is significant: at 1 MPa internal pressure, the difference in maximum displacements is about 0.1 mm and the difference in maximum stresses is about 4 MPa between the heaviest and the lightest bottles.

3.3. Comparison of the experimental top-load strength with the simulation

According to the local manufacturers of CSD bottles, the minimum top-load strength requirement for 1.5 litre CSD bottles is 196 N which corresponds to a compression force equal to the weight of approximately 15 bottles filled up with water. Therefore, in this study, minimum requirement for the top load strength of the bottles was set at 200 N.

Simulation results shown in Figure 4 were analysed with respect to the actual top load strength of the 1.5 litre CSD bottle (40 g preform) which was found to be 307 N [8].

The maximum stress reaches 3.038 MPa when the lightest bottle (37 g preform) is simulated under a 200 N top-load. Although this stress is higher for lighter bottles, nevertheless it is still much lower than the 4.344 MPa critical stress recorded for the heaviest bottle (40 g preform) under the actual buckling load of 307 N. Based on this comparative analysis, all the light-weight bottles considered in this study are expected to pass the minimum 200 N top-load strength requirement without buckling.

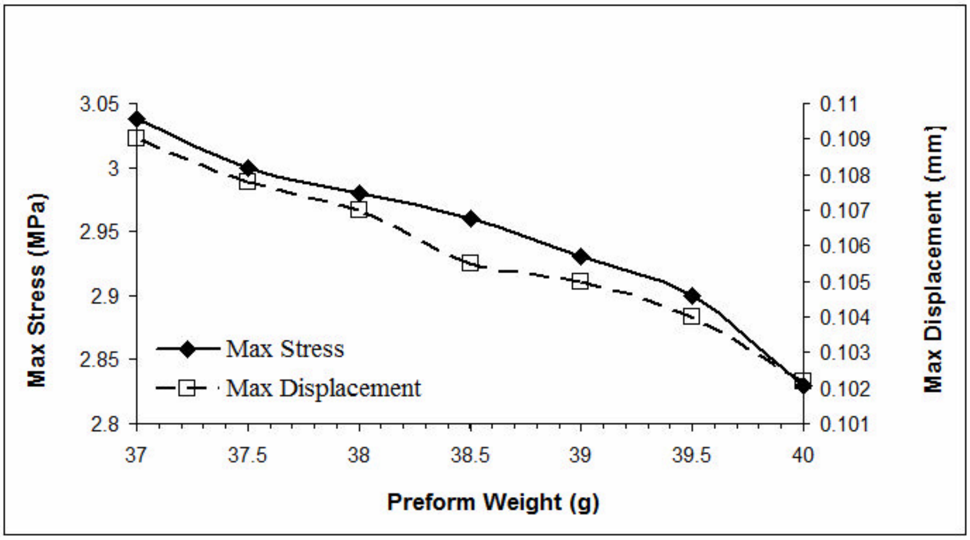

Fig. 4: The maximum stresses and displacement values under 200 N top-load

3.4. Comparison of the experimental burst strength with the simulation

According to the local manufacturers of CSD bottles, minimum burst strength requirement for the 1.5 litre CSD bottles is 0.95 MPa which is well above the internal carbonation pressure of 0.4 to 0.6 MPa recorded for such bottles. Hence, in this study, minimum requirement for the burst strength of the bottles was set at 1 MPa. Simulation results shown in Figure 5 were analysed with respect to the actual burst strength of the 1.5 litre CSD bottle (40 g preform) which was found to be 1.4 MPa [8].

When the lightest bottle (37 g preform) is simulated under an internal pressure of 1 MPa, the maximum stress reaches 107.8 MPa. Although for a given top loading condition, the maximum stress is higher for lighter bottles, this stress is still well below the critical value of 145.2 MPa recorded for the heaviest bottle (40 g) under the actual burst strength of 1.4 MPa. Based on this comparative analysis, all the light-weight bottles considered in this study are expected to pass the 1 MPa minimum burst strength requirement of the packaging industry.

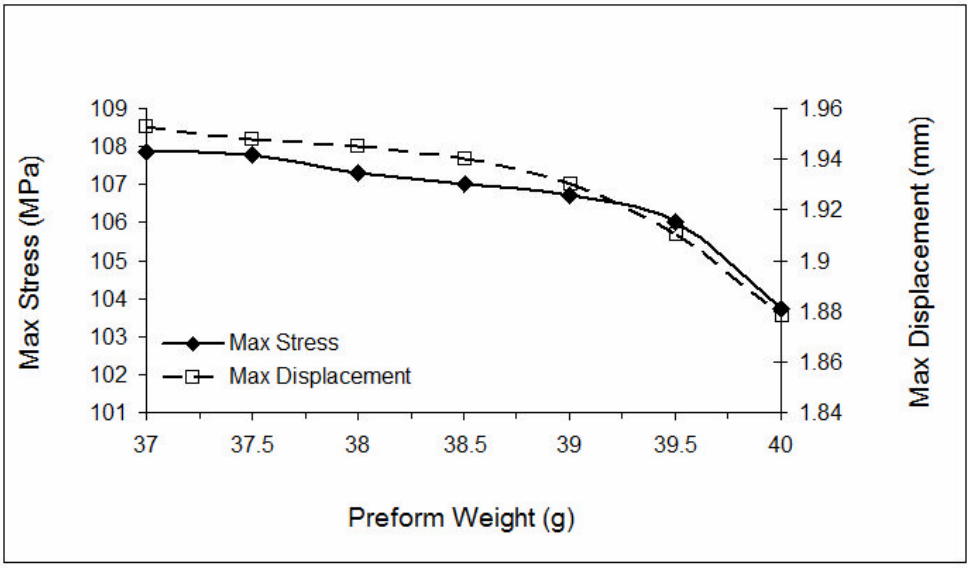

Fig. 5: The maximum stresses and displacement values at 1 MPa internal pressure

4. Materials and energy savings

In 2010, Australian market size for beverage packaging was recorded as 100,500 tonnes of polymer generating 5,000 million containers with an estimated value of 523 million Australian Dollars. Carbonated soft drinks accounted approximately half of the polymer consumption used for beverage packaging with 52,100 tonnes of polymer, resulting in 2,761 million containers valued at 268 million Australian dollars. Whereas, the 1.5 litre blow molded bottles made out of PET generated 572 million carbonated beverage containers, consuming a total of 23,108.8 tonnes of PET. This accounts for approximately 50% of the total blow moulded bottles which is equivalent to 48,583 tonnes of PET [9].

In our study we demonstrated that 3 g weight reduction from 40 g bottles down to 37 g is possible without affecting the functional properties of the bottles particularly in terms of top-load and burst strength. By saving 3 g per 40 g of PET bottle, 7.5% reduction in total material could be achieved. This would be equivalent to 1,733.16 tonnes of PET material for the 1.5 litre carbonated soft drink bottles consumed in Australia alone. Energy is embodied in PET resin itself and additional energy is required for melting the PET and processing the final plastics bottle. It is estimated that 6.48 – 7.69 kWh energy is required for producing the 1 kg of PET resin itself and an additional 1.86 kWh of energy is required for processing of 1 kg of PET into bottles [10]. Hence a weight reduction of 3 g for each 1.5 litre CSD PET bottle is estimated to bring about energy savings of 16,529,236.76 kWh based on the 2010 Australian market size. Greenhouse gas emission can be calculated according to 1 kg of CO_2 per kWh of electricity consumption for Australia to demonstrate the light weighting of bottles not only reduces the materials and energy consumption but also reduces the green house gas emissions.

5. Conclusions

PET bottles are widely used in CSD packaging applications. Any reduction in the amount of PET material used for the CSD bottles could save materials and manufacturing costs. In this study, BlowView simulation software was used to simulate the stretch blow molding of seven preform models of different weights. The simulation results in terms of bottle thickness profiles and microstructure dependant elastic modulus and yield strength values were then exported into ANSYS software for top-load and burst strength analysis. As the preform weight decreases the bottle base becomes thinner.

Although, the reduction in preform weight results in lower thickness particularly in the base of the bottles, the light weight bottles still perform as well as the current 40 g preform bottle. The simulation results show that the lighter bottles (down to 37 g) are able to fulfil the industry requirements in terms of top-load and burst strength. Light weighing of 1.5 litre CSD bottles made out of PET not only reduces the materials and energy consumption but also reduces the green house gas emissions. Similar calculations for all plastics bottles made for worldwide consumption would demonstrate the energy implications of the light weighting of plastics bottles.

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